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## Directional Modulation Enabled Physical-layer Wireless Security

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## Chapter 3

# Directional Modulation Enabled Physical-layer Wireless Security

*Yuan Ding and Vincent Fusco*

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Directional modulation (DM), as a promising keyless physical-layer security technique, has rapidly developed within the last decade. This technique is able to directly secure wireless communications in the physical layer by virtue of the property of its direction-dependent signal modulation formatted transmission. This chapter reviews the development in DM technology over recent years, and provides some recommendations for future studies.

### 3.1 Directional Modulation (DM) Concept

DM concept was first proposed in the antenna and propagation community [1–3]. Normally signal modulations are conducted at digital baseband in conventional communication systems. At that time researchers found that when signal modulations were performed at radio frequency (RF) stages, e.g., antenna array radiation structures [1, 2] and phases of RF carriers feeding into antenna arrays [3], the signal waveforms radiated along different spatial directions in free space were differently combined. In other words, signal modulation formats were direction dependent. This is due to the fact that the far-field radiation patterns produced by each array element are summed differently along different directions, i.e., spatially dependent. When carefully designed, signal waveforms containing required information can be generated along an a-priori selected secured communication direction. In this way only receivers located along the pre-specified direction are able to capture the correct signal signature, leading to successful data recovery, while distorted signal waveforms radiated along other directions make eavesdropping difficult. In order to clearly illustrate the DM concept, take as an example a DM system modulated for quadrature phase-shift keying (QPSK), as shown in Fig. 3.1. Here the standard formatted QPSK constellation patterns, i.e., central-symmetric square in in-phase and quadrature (IQ) space, is preserved only along an a-priori defined observation direction  $\theta_0$ , while along all other spatial directions the signal formats are distorted. In such a fashion, potential eavesdroppers positioned along all other directions suffer a significantly reduced possibility of successful interception.

## 2 Directional Modulation Technology

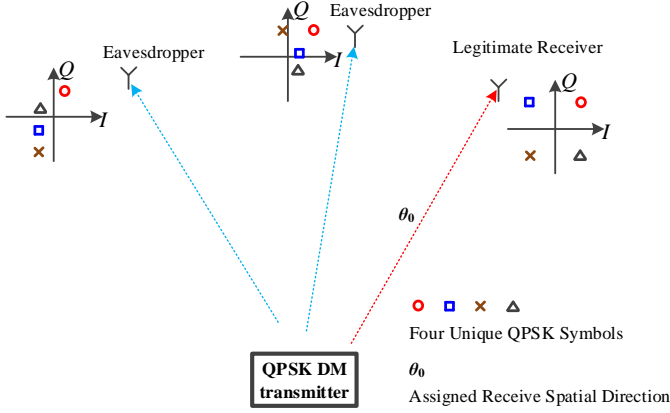


Figure 3.1: Illustration of the major properties of a QPSK DM system. Along a pre-specified direction  $\theta_0$  a usable constellation is formed. Away from the desired direction the constellations are scrambled [4]. (©2015 Cambridge University Press and the European Microwave Association. Reprinted with permission from Ding Y. and Fusco V. “A review of directional modulation technology”. *International Journal of Microwave and Wireless Technologies*. 2015;1-13)

This DM feature is quite distinct from the general broadcast nature normally associated with a conventional wireless transmission system where identical copies, subject to amplitude differences, of signal waveforms are projected into the entire radiation coverage space.

At first it was wrongly believed that the property of the direction dependent modulation transmission was obtained because the signal modulation occurred at the RF stages [1, 2]. In fact in some reported DM transmitters signal modulation still takes place at digital baseband [5]. It was discovered that

- from the antenna and propagation perspective, the essence of the DM technique requires updating antenna array far-field radiation patterns at transmission symbol rates. In contrast, in conventional wireless transmission systems the far-field radiation patterns of antenna or antenna arrays are updated at channel block fading rates.
- from the signal processing perspective, the essence of the DM technique is injecting artificial interference that is orthogonal, in the spatial domain, to the information signal conveyed to the desired receiver [6, 7]. In contrast, in conventional wireless transmission systems no orthogonal artificial interference is used.

The remaining sections in this chapter are organized as follows: in Section 3.2 types of DM transmitter physical architecture are presented and categorised, while a general mathematical model is established in Section 3.3. Section 3.4 describes DM synthesis approaches associated with different types of DM architectures, and the

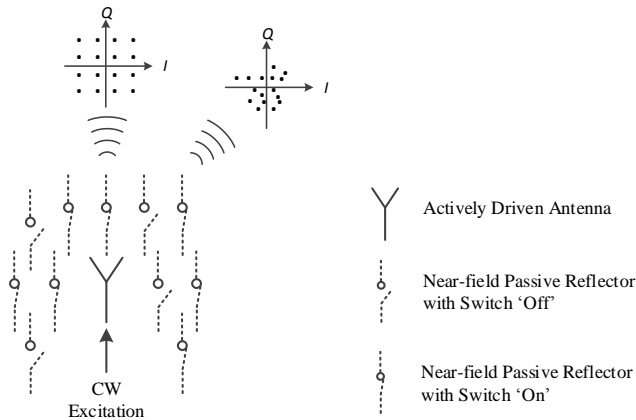
metrics for assessing secrecy performance of DM systems are briefly presented and summarised in Section 3.5. The extension of the DM technique for multi-beam and multipath applications is investigated in Section 3.6. DM demonstrators reported to date are discussed in Section 3.7. Finally, the recommendations for future DM studies are provided in Section 3.8.

## 3.2 DM Transmitter Architectures

In this section we firstly describe the reported DM transmitter architecture in chronological order, and then categorise them into three groups in order to facilitate discussions of their respect properties.

### *A Near-field Direct Antenna Modulation*

The first type of DM transmitter, named by the authors as near-field direct antenna modulation (NFDAM), consists of a large number of reconfigurable passive reflectors coupled in the near field of a centre-driven antenna [1, 8]. The concept of the NFDAM DM transmitter is shown in Fig. 3.2. Each set of switch state combinations on the near-field passive reflectors contributes to a unique far-field radiation pattern, which can be translated into constellation points in IQ space detected along each spatial direction in free space. After measurement of a multiplicity of patterns, with regard to a large number of possible switch combinations, has been done, a usable constellation pattern detected along the desired direction may be selected. Subsequently the corresponding switch settings for secure transmission of each symbol is memorised in order to reproduce this usable state. Since the far-field patterns associated with each selected switch combination are different functions of the spatial direction, the detected signal constellation patterns along undesired communication directions are distorted.



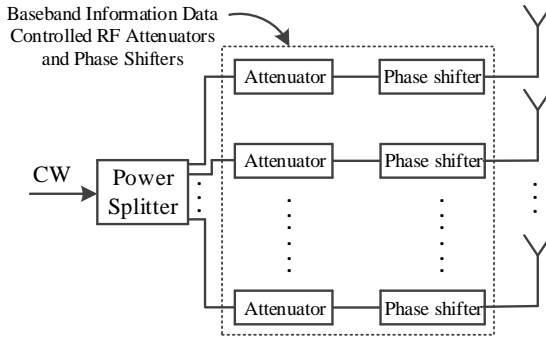
*Figure 3.2: Concept of NFDAM DM structure.*

### *B DM Using Reconfigurable Antennas in an Array Configuration*

Similar to the NFDAM, by replacing each antenna element, both the central active-driven antenna and the surrounding passive reflectors, with an active-driven pattern reconfigurable antenna element, a DM transmitter can also be constructed [2]. When the array elements are well separated, e.g., half wavelength spaced, the current on antenna elements can be actively manipulated using the reconfigurable components associated with each of the antenna radiation structures. Performance optimisation of the DM transmitter proceeds using optimisation algorithms [3, 9].

### *C DM Using Phased Antenna Array*

In [3] the authors built a DM transmitter using a phased antenna array, see Fig. 3.3. This type of architecture exploits individual array element excitation re-configurability, instead of radiation structure re-configurability, in order to achieve direction dependent modulation transmission. This excitation-reconfigurable DM structure has then been heavily investigated under various hardware constraints [9–13] mainly because it is synthesis-friendly and it can be readily implemented.



*Figure 3.3: Generic excitation-reconfigurable DM transmitter array [4]. (©2015 Cambridge University Press and the European Microwave Association. Reprinted with permission from Ding Y. and Fusco V. “A review of directional modulation technology”. International Journal of Microwave and Wireless Technologies. 2015;1-13).*

### *D DM Using Fourier Beamforming Networks*

In [14, 15] DM transmitters were constructed using Fourier beamforming networks, e.g., Butler matrix and Fourier Rotman lens, whose orthogonality property in beam space helps project uncontaminated signals only along the selected spatial direction that corresponds to the excited information beam port, Fig. 3.4. This type of DM arrangement reduces the number of required RF chains to two, and it was exper-

imentally verified for 10 GHz operation for real-time data transmission with both analogue and digital modulations in [16] and [7], respectively.

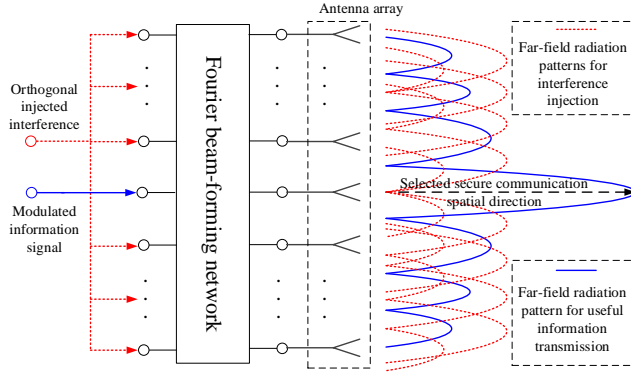


Figure 3.4: Fourier beamforming network enabled DM transmitters.

### E DM Using Switched Antenna Arrays

Researchers in [17, 18] revealed that by inserting a switch array before antennas to randomly select a subset of elements in an antenna array for signal transmission on a per transmitted symbol basis, DM transmitters could have been constructed. Actually this concept had been proposed long before in [19]. This architecture, named as antenna subset modulation (ASM) in [17] or 4-D antenna arrays in [20], requires only one RF chain the expense of reduced beamforming gain.

### F DM Using Digital Baseband

The DM transmitter in Fig. 3.3 uses RF components to reconfigure antenna array excitations. It is natural to replace these RF components with more flexible and more precise digital baseband arrangements [6, 21]. This approach facilitates the DM technique being applied in modern digital wireless communication systems [5].

The above mentioned types of DM architecture can be sorted into three categories, namely, radiation structure reconfigurable DM (*A* and *B*), excitation reconfigurable DM (*C* and *F*), and synthesis-free DM (*D* and *E*, as well as retrodirective DM in [22]). Their individual characteristics are summarised in Table 3.1. Since the design of radiation structure reconfigurable DM is greatly dependent on the selected antenna structure, no effective universal synthesis methods are available. While the synthesis-free DM can be considered as hardware realisation of some excitation reconfigurable DM. As a consequence, only the details for the excitation reconfigurable DM are provided later in this chapter.

*Table 3.1: Summary of characteristics of different types of DM architecture*

	Radiation Structure Reconfigurable DM		Excitation Reconfigurable DM		Synthesis-free DM	
	<i>A</i>	<i>B</i>	<i>C</i>	<i>F</i>	<i>D</i>	<i>E</i>
Synthesis	Difficult		Medium	Easy	Not Required	
Optimisation <sup>a</sup>	Difficult		Medium	Easy	Medium	
Multi-beam <sup>b</sup>	Difficult		Medium		Easy	Difficult
Multipath	Difficult		Medium	Easy	Difficult	
System Complexity	High		High	Medium	Low	Medium
Cost	High		High	Medium	Low	

*a*: It refers to the enhancement of the system secrecy performance

*b*: It refers to secure independent transmission along multiple spatial directions simultaneously

### 3.3 Mathematical Model for DM

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In order to facilitate the synthesis of DM transmitters, a mathematical model was established in [6, 23]. This model is the key to understanding the essence of the DM technique presented in Section 3.1, and thus is elaborated as below.

The superimposed radiation from a series of radiating antenna elements in free space can be formed for  $N$  elements, with the summed far-field radiation pattern  $\mathbf{P}$  at some distant observation point in free space, given as

$$\mathbf{P}(\theta) = \frac{e^{-j\vec{k}\cdot\vec{r}}}{|\vec{r}|} \begin{bmatrix} \mathbf{R}_1(\theta) \\ \mathbf{R}_2(\theta) \\ \vdots \\ \mathbf{R}_N(\theta) \end{bmatrix} \cdot \begin{bmatrix} \mathbf{A}_1 e^{-j\vec{k}\cdot\vec{x}_1} \\ \mathbf{A}_2 e^{-j\vec{k}\cdot\vec{x}_2} \\ \vdots \\ \mathbf{A}_N e^{-j\vec{k}\cdot\vec{x}_N} \end{bmatrix}, \quad (3.1)$$

where  $\mathbf{R}_n$  ( $n \in (1, 2, \dots, N)$ ) refers to the far-field active element pattern of the  $n^{th}$  array element, which is a function of spatial direction  $\theta$ .  $\mathbf{A}_n$  is the excitation applied at the  $n^{th}$  antenna port.  $\vec{k}$  is the wavenumber vector along each spatial direction  $\theta$ .  $\vec{r}$  and  $\vec{x}_n$ , respectively, represent the location vectors of the receiver and the  $n^{th}$  array element relative to the array phase centre.

In a conventional wireless transmitter beamforming array, when the communication direction is known, denoted as  $\theta_0$ , the antenna excitation  $\mathbf{A}_n$  is designed such that  $\mathbf{R}_n(\theta_0)\mathbf{A}_n e^{-j\vec{k}\cdot\vec{x}_n}$  for each  $n$  are in-phase. As a result, the main radiation beam is steered towards the direction  $\theta_0$ . The information data  $\mathbf{D}$ , which is a complex number corresponding to a constellation point in IQ space, can then be identical applied onto each  $\mathbf{A}_n$ , i.e.,  $\mathbf{D}\mathbf{A}_n$ , for wireless transmission with the signal magnitude

spatial distribution governed by  $|\mathbf{P}(\theta)|$ . During the entire data transmission  $\mathbf{P}(\theta)$  is unchanged.

In a DM transmitter array, the information data is wirelessly delivered using more degrees of freedom within the array. The far-field radiation pattern  $\mathbf{P}(\theta)$  in (3.1) does not remain constant during the data stream transmission as occurs in the conventional beamforming system. Instead the pattern  $\mathbf{P}(\theta)$  is differently synthesised for each symbol transmitted.  $\mathbf{P}(\theta_0)$  can be directly designed as  $\mathbf{D}_i$  which is the  $i^{th}$  transmitted symbol, or it can be designed to be a constant value with the required data stream applied afterwards. Both approaches are equivalent. As can be seen in (3.1), there are two ways to alter the far-field pattern  $\mathbf{P}(\theta)$ ; one is to reconfigure the radiation patterns  $\mathbf{R}_n$  of each antenna element, as adopted in the radiation structure reconfigurable DM, and the other is to update the antenna excitations  $\mathbf{A}_n$ , as exploited in the excitation reconfigurable DM, in both cases at the transmission symbol rate. The former method, i.e., altering  $\mathbf{R}_n$ , either passively or actively, is complicated because there is no closed-form link between the geometry of the antenna radiation structure and its far-field radiation pattern. Thus the focus of the DM mathematical model described in this section is on the excitation reconfigurable DM structure, though the model can, in principle, be utilised to analyse the radiation structure reconfigurable DM and the synthesis-free DM.

In order to facilitate discussion and simplify mathematical expressions, isotropic antenna active element patterns, i.e.,  $\mathbf{R}_n(\theta) = 1$ , and uniform one-dimensional (1D) array elements with spacing  $|\vec{x}_{n+1} - \vec{x}_n|$  of one half wavelength ( $\lambda/2$ ) are assumed for the establishment of the DM model. This model can be readily extended for general DM transmitter scenarios, e.g., arbitrary antenna active element patterns and other array arrangements. Under these assumptions the far-field pattern  $\mathbf{P}(\theta)$  is solely determined by the array element excitations  $\mathbf{A}_n$ .

$$\mathbf{P}(\theta) = \sum_{n=1}^N \left( \mathbf{A}_n e^{j\pi(n - \frac{N+1}{2}) \cos \theta} \right) \quad (3.2)$$

The term  $e^{-jk\vec{r}}/|\vec{r}|$  is dropped, because it is a constant complex scaling factor for the pattern  $\mathbf{P}$  in all directions.

Since there are analogue and digital means for updating  $\mathbf{A}_n$  as discussed in Section 3.2, a description technique which is architecture independent and which lends itself to both analysis and synthesis of any class of excitation reconfigurable DM structures is required. Thus the requirements that array excitations  $\mathbf{A}_n$  need to satisfy for a DM transmitter are analysed, regardless of the means of generating  $\mathbf{A}_n$ . For clarity, we add an additional subscript ' $i$ ' to the relevant notations to refer to their updated values in the  $i^{th}$  transmitted symbol slot.

As previously stated, the two key properties of a DM transmitter are

- preservation of the transmitted signal format (standard constellation pattern in IQ space) along a pre-specified communication direction  $\theta_0$ ;
- distortion of constellation patterns along all other communication directions.

From a signal processing perspective,  $\mathbf{P}(\theta)$  in (3.2) can be regarded as a detected constellation point in IQ space at receiver sides, denoted as  $\mathbf{D}_i(\theta)$  for the  $i^{th}$  symbol



transmitted, (3.3)

$$\mathbf{D}_i(\theta) = \sum_{n=1}^N \underbrace{\mathbf{A}_{ni} \cdot e^{j\pi(n-\frac{N+1}{2})\cos\theta}}_{\mathbf{B}_{ni}(\theta)}. \quad (3.3)$$

For each symbol transmitted, the vector summation of  $\mathbf{B}_{ni}$  has to yield the standard constellation point  $\mathbf{D}_i^{st}$  in IQ space along, and only along, the direction  $\theta_0$ . This statement, in mathematical description, can be expressed in (3.4),

$$\sum_{n=1}^N \mathbf{B}_{ni}(\theta_0) = \mathbf{D}_i^{st}. \quad (3.4)$$

From (3.3), by scanning the observation angle  $\theta$ , the constellation track in IQ space,  $\mathbf{D}_i(\theta)$ , of the  $i^{th}$  symbol can be obtained.

General properties of constellation tracks can be observed from (3.3), and are summarised as below:

- a) For an array with an odd number of elements, constellation tracks are closed loci. In some extreme cases, these loci collapse to line segments. The starting point ( $\theta = 0^\circ$ ) always overlaps with end point ( $\theta = 180^\circ$ ). For the case of even number elements,  $\mathbf{D}_i(0^\circ) = -\mathbf{D}_i(180^\circ)$ . When the array element spacing is changed, the start and end angle will change accordingly.
- b) Changing the desired communication direction  $\theta_0$  does not affect the shape of the constellation track pattern in IQ space. It determines only where the tracks start ( $\theta = 0^\circ$ ) and end ( $\theta = 180^\circ$ ).
- c) Different vector paths (trajectories of the vector summation,  $\sum_{n=1}^N \mathbf{B}_{ni}(\theta_0)$ ) inevitably lead to different constellation tracks. This is guaranteed by the orthogonality property of  $e^{jn\pi\cos\theta}$  for different  $n$  within the spatial range from  $0^\circ$  to  $180^\circ$ .
- d) When  $\mathbf{B}_{np}(\theta_0)$  are the scaled  $\mathbf{B}_{nq}(\theta_0)$  with the same scaling factor  $\mathbf{K}$  for each  $n$ , the corresponding constellation track  $\mathbf{D}_p(\theta)$  is also the scaled  $\mathbf{D}_q(\theta)$  with the same scaling factor  $\mathbf{K}$ .

Properties c) and d) above indicate that constellation distortion at other directions can be guaranteed when vector  $[\mathbf{B}_{1p}(\theta_0) \ \mathbf{B}_{2p}(\theta_0) \ \cdots \ \mathbf{B}_{Np}(\theta_0)]$  and the other vector  $[\mathbf{B}_{1q}(\theta_0) \ \mathbf{B}_{2q}(\theta_0) \ \cdots \ \mathbf{B}_{Nq}(\theta_0)]$  are linearly independent, see (3.5). Here the  $p^{th}$  and the  $q^{th}$  symbols in the data stream are different modulated symbols.

$$[\mathbf{B}_{1p}(\theta_0) \ \mathbf{B}_{2p}(\theta_0) \ \cdots \ \mathbf{B}_{Np}(\theta_0)] \neq \mathbf{K} [\mathbf{B}_{1q}(\theta_0) \ \mathbf{B}_{2q}(\theta_0) \ \cdots \ \mathbf{B}_{Nq}(\theta_0)] \quad (3.5)$$

The combination of (3.4) and (3.5) forms the necessary conditions for DM transmitter arrays. Thus, the requirement for the DM array excitations  $\mathbf{A}_{ni}$  can then be obtained using (3.3).

With the DM vector model described above the static and dynamic DM transmitters are defined below [4]. This classification facilitates the discussions of DM synthesis approaches that are presented in Sections 3.4.

**Definition:** If along the DM secure communication direction the vector path in IQ space reaching each unique constellation point is independent and fixed, which results in a distorted, but static with respect to time, constellation pattern along other spatial directions, the transmitters are termed ‘static DM’; if the vector paths are randomly re-selected, on a per transmitted symbol basis in order to achieve the same constellation symbol in the desired direction, then the symbol transmitted at the different time slots in the data stream along spatial directions other than the prescribed direction would be scrambled dynamically and randomly. This we call the ‘dynamic DM’ strategy.

With the above definition the DM transmitters reported in [1–3, 8–12] fall into the static DM category, while the DM systems reported in [5–7, 14, 15, 17, 20], involving time as a variable to update system settings, can be labeled as dynamic.

It is noted that here we assume the potential eavesdroppers located along directions other than the intended secure communication direction do not collude. For the colluding eavesdroppers, especially when the number of colluding eavesdroppers are greater than the number of DM transmit array elements, the successful estimation of the useful information conveyed to the desired receivers is possible. Thus a different system design rules should be adopted. Interested readers can find more details on this aspect in [21], where DM system is viewed and analysed from a signal processing perspective.

### 3.4 Synthesis Approaches for DM Transmitters

As discussed in Section 3.2, the design of the radiation structure reconfigurable DM is complicated due to the lack of closed-form link between the geometry of the antenna radiation structure and its far-field radiation pattern. Seeking DM synthesis approaches for the excitation reconfigurable DM transmitter architecture is the most active area in DM research recently. Among all synthesis approaches, the orthogonal vector method developed in [6, 24], which shares a similar idea with the artificial noise concept [25, 26] studied in the information theory community, was found to furnish a fundamental and universal DM synthesis strategy. It also provides the key to understand the synthesis-free DM architecture. Thus the orthogonal vector synthesis approach is next elaborated in this section.

#### 3.4.1 Orthogonal Vector Approach for DM Synthesis

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In Section 3.3, it is showed that when the same constellation symbol detected along the desired communication direction is reached via different vector paths in IQ space, the resulting constellation tracks are altered accordingly. This leads to the constellation pattern distortion along spatial directions other than the prescribed direction, which is the key property of DM systems. In other words, it is the difference between each two vector paths selected to achieve a same standard constellation point in IQ space that enables DM behaviour. This difference is defined as the orthogonal vector, since it is always orthogonal to the conjugated channel vector along the intended spatial direction.

A one-dimensional (1D) five-element array with half wavelength spacing is taken as an example below in order to explain the orthogonal vector concept. It is assumed that each antenna element has an identical isotropic far-field radiation pattern.

The channel vector for this system along the desired communication direction  $\theta_0$  in free space can be written as

$$\vec{H}(\theta_0) = \left[ \underbrace{e^{j2\pi \cos \theta_0}}_{H_1} \quad \underbrace{e^{j\pi \cos \theta_0}}_{H_2} \quad \underbrace{e^{j0}}_{H_3} \quad \underbrace{e^{-j\pi \cos \theta_0}}_{H_4} \quad \underbrace{e^{-j2\pi \cos \theta_0}}_{H_5} \right]^T, \quad (3.6)$$

where  $[\cdot]^T$  refers to the transpose operator.

When the excitation signal vectors  $[A_{1i}(\theta_0) \ A_{2i}(\theta_0) \ \cdots \ A_{Ni}(\theta_0)]^T$  at the array input for the same symbol transmitted at the  $u^{th}$  and  $v^{th}$  time slots chosen to be

$$\vec{S}_u = \left[ \underbrace{e^{j(-\frac{\pi}{4} + 2\pi \cos \theta_0)}}_{S_{1u}} \quad \underbrace{e^{j\pi \cos \theta_0}}_{S_{2u}} \quad \underbrace{e^{j0}}_{S_{3u}} \quad \underbrace{e^{-j\pi \cos \theta_0}}_{S_{4u}} \quad \underbrace{e^{-j2\pi \cos \theta_0}}_{S_{5u}} \right]^T \quad (3.7)$$

and

$$\vec{S}_v = \left[ \underbrace{e^{j(\frac{\pi}{4} + 2\pi \cos \theta_0)}}_{S_{1v}} \quad \underbrace{e^{j(\frac{\pi}{4} + \pi \cos \theta_0)}}_{S_{2v}} \quad \underbrace{e^{-j\frac{\pi}{4}}}_{S_{3v}} \quad \underbrace{e^{j(\frac{3\pi}{4} - \pi \cos \theta_0)}}_{S_{4v}} \quad \underbrace{e^{j(\frac{\pi}{4} - 2\pi \cos \theta_0)}}_{S_{5v}} \right]^T, \quad (3.8)$$

the resulting received vector paths in IQ space along this spatial direction  $\theta_0$  are

$$\begin{aligned} \vec{B}_u &= \vec{H}^*(\theta_0) \circ \vec{S}_u \\ &= \left[ \underbrace{H_1^* \cdot S_{1u}}_{B_{1u}} \quad \underbrace{H_2^* \cdot S_{2u}}_{B_{2u}} \quad \underbrace{H_3^* \cdot S_{3u}}_{B_{3u}} \quad \underbrace{H_4^* \cdot S_{4u}}_{B_{4u}} \quad \underbrace{H_5^* \cdot S_{5u}}_{B_{5u}} \right]^T \\ &= \left[ e^{-j\frac{\pi}{4}} \quad e^{j\frac{\pi}{4}} \quad e^{j\frac{\pi}{4}} \quad e^{j\frac{\pi}{4}} \quad e^{j\frac{3\pi}{4}} \right]^T \end{aligned} \quad (3.9)$$

and

$$\begin{aligned} \vec{B}_v &= \vec{H}^*(\theta_0) \circ \vec{S}_v \\ &= \left[ \underbrace{H_1^* \cdot S_{1v}}_{B_{1v}} \quad \underbrace{H_2^* \cdot S_{2v}}_{B_{2v}} \quad \underbrace{H_3^* \cdot S_{3v}}_{B_{3v}} \quad \underbrace{H_4^* \cdot S_{4v}}_{B_{4v}} \quad \underbrace{H_5^* \cdot S_{5v}}_{B_{5v}} \right]^T \\ &= \left[ e^{j\frac{\pi}{4}} \quad e^{j\frac{\pi}{4}} \quad e^{-j\frac{\pi}{4}} \quad e^{j\frac{3\pi}{4}} \quad e^{j\frac{\pi}{4}} \right]^T, \end{aligned} \quad (3.10)$$

where  $[\cdot]^*$  returns the conjugation of the enclosed term, and operator  $\circ$  denotes Hahamard product of two vectors. These vector paths described in (3.9) and (3.10) are plotted in Fig. 3.5.

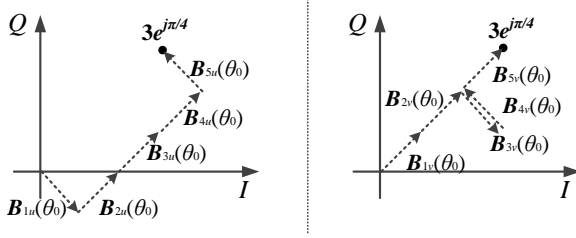


Figure 3.5: Illustration example of two vector paths derived from two different excitation settings [4]. (©2015 Cambridge University Press and the European Microwave Association. Reprinted with permission from Ding Y. and Fusco V. “A review of directional modulation technology”. *International Journal of Microwave and Wireless Technologies*. 2015;1-13)

The vector summations of  $\sum_{n=1}^5 \mathbf{B}_{nu}$  and  $\sum_{n=1}^5 \mathbf{B}_{nv}$  can be calculated by  $\vec{\mathbf{H}}^\dagger(\theta_0)\vec{\mathbf{S}}_u$  and  $\vec{\mathbf{H}}^\dagger(\theta_0)\vec{\mathbf{S}}_v$ , both reading position  $3 \cdot e^{j\pi/4}$  in IQ space.  $(\cdot)^\dagger$  denotes complex conjugate transpose (Hermitian) operator.

The difference between the corresponding two excitation signal vectors is the orthogonal vector

$$\begin{aligned} \Delta\vec{\mathbf{S}} &= \vec{\mathbf{S}}_v - \vec{\mathbf{S}}_u \\ &= \sqrt{2} \begin{bmatrix} e^{j(\frac{\pi}{2} + 2\pi \cos \theta_0)} & 0 & e^{-j\frac{\pi}{2}} & e^{j\pi(1 - \cos \theta_0)} & e^{-j2\pi \cos \theta_0} \end{bmatrix}^T, \end{aligned} \quad (3.11)$$

which is orthogonal to the conjugated channel vector  $\vec{\mathbf{H}}^*(\theta_0)$  since  $\vec{\mathbf{H}}^*(\theta_0) \cdot \Delta\vec{\mathbf{S}} = 0$ .

With the help of the orthogonal vector concept, a generalised DM synthesis approach was developed in [6] and further refined in [27]. The synthesised DM transmitter array excitation vector  $\vec{\mathbf{S}}_{ov}$  takes the form

$$\vec{\mathbf{S}}_{ov} = \vec{\Lambda} + \vec{\mathbf{W}}_{ov}, \quad (3.12)$$

where  $\vec{\Lambda}$  is a vector with each entry of array excitations before injecting the orthogonal vector  $\vec{\mathbf{W}}_{ov}$  that is orthogonal to the conjugated channel vector  $\vec{\mathbf{H}}^*(\theta_0)$ . Denote  $\vec{\mathbf{Q}}_p$  ( $p = 1, 2, \dots, N-1$ ) to be the orthonormal basis in the null space of  $\vec{\mathbf{H}}^*(\theta_0)$ , then  $\vec{\mathbf{W}}_{ov} = 1/(N-1) \sum_{p=1}^{N-1} (\vec{\mathbf{Q}}_p \cdot \mathbf{v}_p)$ .  $\mathbf{v}_p$  is a random viable used to control the power of the injected orthogonal vector  $\vec{\mathbf{W}}_{ov}$ . Here,  $\vec{\Lambda}$  is defined as the excitations of non-DM beam steering arrays, selected according to the system requirements, e.g., uniform magnitude excitations used in conventional beam steering phased arrays result in narrower secure transmission spatial region, while other magnitude-tapered excitations can reduce the amount of leaked information through sidelobe directions at the

cost of slightly widened secure transmission spatial region. This excitation contains the information symbol  $\mathbf{D}_i$  to be transmitted, e.g.,  $e^{j\pi/4}$  corresponds to the QPSK symbol 11.

During the synthesis of DM arrays from the non-DM beam steering arrays two parameters which are crucial to system performance, need to be discussed. One is the length of each excitation vector. From a practical implementation perspective, the square of the excitation vector should fall into the linear range of each power amplifier located within each RF path. The other is the extra power that is required to be injected into the non-DM array in order for signal distortion along other directions.

In order to describe this extra power, the DM power efficiency ( $PE_{DM}$ ) is defined:

$$PE_{DM} = \frac{\sum_{i=1}^I \left( \sum_{n=1}^N |\Lambda_{ni}|^2 \right)}{\sum_{i=1}^I \left( \sum_{n=1}^N |S_{ov,ni}|^2 \right)} \times 100\% = \frac{\sum_{i=1}^I \left( \sum_{n=1}^N |\mathbf{B}_{ni,nonDM}|^2 \right)}{\sum_{i=1}^I \left( \sum_{n=1}^N |\mathbf{B}_{ni,DM}|^2 \right)} \times 100\%, \quad (3.13)$$

where  $I$  is, for static DM, the number of modulation states, e.g., 4 for QPSK, or, for dynamic DM, the symbol number  $T$  in a data stream.  $\Lambda_{ni}$  and  $S_{ov,ni}$  are the  $n^{th}$  array element excitation for the  $i^{th}$  symbol in the non-DM array and in the synthesised DM array, respectively. In noiseless free space, their modulus equal to the normalized modulus of corresponding  $\mathbf{B}_{ni,nonDM}$  and  $\mathbf{B}_{ni,DM}$  from the receiver side perspective. Generally, the larger the allowable range of the excitation vector lengths are, and the lower  $PE_{DM}$  is, the better the DM system secrecy performance that can be achieved.  $PE_{DM}$  can also be expressed as a function of  $v_p$  as in (3.14) and (3.15),

$$PE_{DM} = \frac{1}{I} \cdot \sum_{i=1}^I PE_{DM,i}, \quad (3.14)$$

$$PE_{DM,i} = \frac{1}{1 + \sum_{p=1}^{N-1} \left( \frac{1}{N-1} \cdot v_p \right)^2} \times 100\%. \quad (3.15)$$

### 3.4.2 Other DM Synthesis Approaches

In the last subsection, the universal DM synthesis method, i.e., the orthogonal vector approach, is presented. However, in some application scenarios, some other requirements on DM system properties may need to be considered. These requirements, or constraints, which have been investigated, include the bit error rate (BER) spatial distribution, the array far-field radiation characteristics, and the interference spatial distribution. All these synthesis methods can be viewed as seeking a subset of orthogonal vectors that satisfy prescribed DM system requirements.

The BER-driven [28] and the constrained array far-field radiation pattern [29–31] DM synthesis approaches share a similar idea, i.e., via the iterative transformations between the array excitations and the required DM properties, namely the BER spatial distributions and the array far-field radiation patterns, the constraints on DM

characteristics can be imposed. Since iteration processes are involved, these two methods are not suitable for dynamic DM synthesis.

Another DM array far-field pattern separation synthesis approach was developed in [32, 33]. Here by virtue of the far-field null steering approach, the DM array far-field radiation patterns can be separated into information patterns, which describe information energy projected along each spatial direction, and interference patterns, which represent disturbance on genuine information. Through this separation methodology, we can identify the spatial distribution of information transmission and hence focus interference energy into the most vulnerable directions with regard to interception, i.e., information sidelobes, and in doing so submerge leaked information along unwanted directions. This method is closely linked to the orthogonal vector approach. In fact, the separated interference patterns can be considered as far-field patterns generated by the injected orthogonal vectors. However, it is more convenient to apply constraints, such as interference spatial distribution, with the pattern separation approach. This approach is compatible to both static and dynamic DM systems.

The relationships among the four DM synthesis approaches are illustrated in Fig. 3.6.

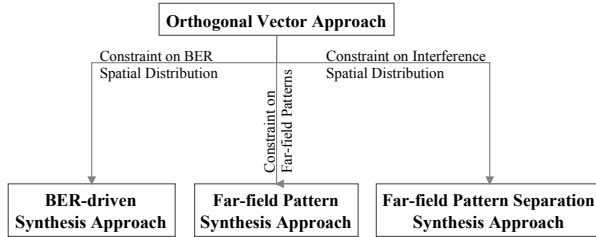


Figure 3.6: Relationships among the four DM synthesis approaches [4]. (©2015 Cambridge University Press and the European Microwave Association. Reprinted with permission from Ding Y. and Fusco V. “A review of directional modulation technology”. *International Journal of Microwave and Wireless Technologies*. 2015;1-13)

Through the various DM synthesis approaches presented above and their associated examples, it is found that DM functionality is always enabled by projecting extra energy into undesired communication directions in free space. This extra energy, which can be either static or dynamic with respect to time, corresponding to static and dynamic DM systems, acts as interference which scrambles constellation symbol relationships along the unselected directions. Intuitively, the larger the interference energy projected, the more enhanced the DM system secrecy performance that can be achieved. It is concluded that the essence of a functional DM system synthesis approaches lies in generating artificial interference energy that is orthogonal to the directions where the intended receivers locate.

### 3.4.3 A Note on Synthesis-free DM Transmitters

Two types of synthesis-free DM transmitters have been reported to date. They are the Fourier beamforming network assisted DM [7] and the ASM [17], as described in Section 3.2. Their ‘synthesis-free’ property is enabled by the adopted hardware, i.e., Fourier beamforming network and antenna subset selection switches, which has the capability of generating orthogonal vectors without additional calculation for interference projection along all undesired spatial directions.

In addition to the above two types of synthesis-free DM transmitters, another promising synthesis-free DM architecture that is based on the retrodirective arrays (RDAs) [34] has yet been reported. This RDA-enabled DM transmitter is able to overcome the weaknesses inherent in the Fourier beamforming network and the ASM DM systems, which are

- transmitters need to acquire receiver’s direction in advance;
- in the Fourier beamforming network assisted DM systems, receivers can only locate at some discrete spatial directions in order to maintain orthogonality between information and artificial interference. The number of these spatial directions and their angular spacings are determined by the number of array elements;
- in the ASM DM systems, the available transmission gain is greatly reduced because only a small subset of antennas in the array are utilised for beamforming.

An RDA is capable of re-transmitting signals back along the spatial direction along which the array was interrogated by the incoming signals without requiring a-priori knowledge of its direction of arrival. In order to achieve retrodirective re-transmit functionality, a phase conjugator (PC) is required [35]. Next we discuss how a classical RDA is altered to form a synthesis-free DM transmitter. The system block diagram associated with this is illustrated in Fig. 3.7.

In the receive (Rx) mode the pilot tone signal from a legitimate receiver along  $\theta_0$  in free space impinged on the antenna array with  $N$  elements is phase conjugated. The phase conjugated signal can be expressed as a vector  $\vec{J}$ , of which the  $n^{th}$  entry is  $J_n = H_n^*(\theta_0)$ , seen in Fig. 3.7.  $H_n(\theta_0)$  is the channel coefficient between the distant receiver and the  $n^{th}$  RDA element, which for the RDA arrangement in Fig. 3.7 is  $e^{-j\pi(n-\frac{N+1}{2})\cos\theta_0}$  after the path loss is normalized.

In a classical RDA the phase conjugated  $\vec{J}$  is directly used for re-transmission, i.e.,  $\vec{E} = \vec{J}$ . Here  $\vec{E}$ , as well as  $\vec{H}$ ,  $\vec{C}$ , and  $\vec{L}$  that will be used later in this subsection, is defined similarly as  $\vec{J}$ . In this case the distant pilot source node receives

$$F = \vec{H}(\theta_0) \cdot \vec{E} = \vec{H}(\theta_0) \cdot \vec{J} = \vec{H}(\theta_0) \cdot \vec{H}^*(\theta_0) = N, \quad (3.16)$$

which indicates the perfect beamforming towards the legitimate receiver. However, as was pointed out in Section 3.1 this classical beamforming preserves the signal formats in all radiation directions.

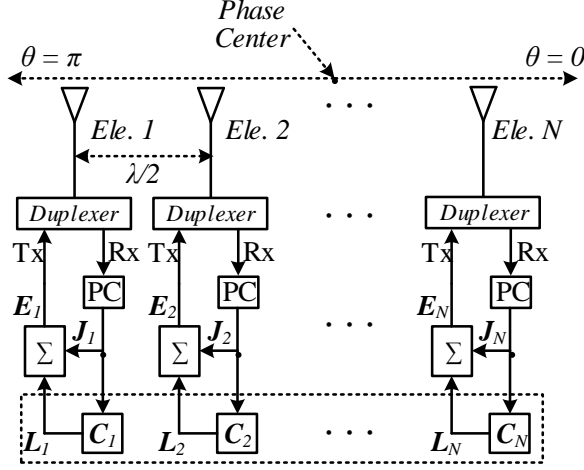


Figure 3.7: Architecture of synthesis-free RDA DM transmitter.

By adding an extra block, enclosed within the dotted box in Fig. 3.7, the synthesis-free DM can be constructed. Its operation is elaborated as below.

With the additional enclosed block, the received signal along  $(\theta_0)$  is

$$\mathbf{F} = \vec{\mathbf{H}}(\theta_0) \cdot \vec{\mathbf{E}} = \vec{\mathbf{H}}(\theta_0) \cdot (\vec{\mathbf{J}} + \vec{\mathbf{L}}) = N + \vec{\mathbf{H}}(\theta_0) \cdot (\vec{\mathbf{C}} \circ \vec{\mathbf{J}}) = N + \vec{\mathbf{C}} \cdot (\vec{\mathbf{H}}(\theta_0) \circ \vec{\mathbf{J}}). \quad (3.17)$$

Since  $\vec{\mathbf{H}}(\theta_0) \circ \vec{\mathbf{J}} = \vec{\mathbf{H}}(\theta_0) \circ \vec{\mathbf{H}}^*(\theta_0)$  is a vector with all  $N$  elements of unity, (3.17) can be written as

$$\mathbf{F} = N + \sum_{n=1}^N \mathbf{C}_n. \quad (3.18)$$

From (3.18) it can be seen that when  $\sum_{n=1}^N \mathbf{C}_n$  is kept as a constant during the entire data transmission, the formats of re-transmitted information signal  $\mathbf{D}$ , applied onto  $\vec{\mathbf{E}}$  afterwards, can be well preserved along  $\theta_0$ , i.e.,  $\mathbf{F}\mathbf{D}$ . However, along all other directions the signal formats are scrambled due to the randomly updated  $\vec{\mathbf{C}}(\vec{\mathbf{H}}(\theta) \circ \vec{\mathbf{J}})$ ,  $(\theta \neq \theta_0)$ . As a consequence, a synthesis-free DM transmitter can be successfully realised.

### 3.5 Assessment Metrics for DM Systems

In order to evaluate the performance of DM systems in a way that is consistent and which allows direct comparison between different systems, assessment metrics were systematically investigated in [36]. It was shown that for static DM systems BER, calculated from either closed-form equations or random data streams, as well



as secrecy rate were applicable for system performance evaluation, whereas error-vector-magnitude-like (EVM-like) metrics did not perform well. For dynamic DM systems under the scenarios of zero-mean Gaussian distributed orthogonal interference, EVM-like metrics, BER, and secrecy rate were equivalent and can be converted between each other. For other interference distributions no closed-form BER and secrecy rate equations were found.

In order to provide readers with a clear picture on metrics for assessing performance of DM systems, all of the findings presented in [36] are summarized in Table 3.2.

*Table 3.2: Summaries of Metrics for DM System Performance Assessment [37]. (©2015 Cambridge University Press and the European Microwave Association. Reprinted with permission from Ding Y. and Fusco V. “A review of directional modulation technology”. International Journal of Microwave and Wireless Technologies. 2015;1-13)*

		EVM	BER		Secrecy rate	
			Closed form equation	Data stream simulation	Numerical calculus	Bit-wise [38]
Static DM		—	•	+	+	—
Dynamic DM	Zero-mean Gaussian orthogonal vectors	+	•	+	+	+
	Zero-mean non-Gaussian orthogonal vectors	—	—	+	—	—
	Non-zero-mean orthogonal vectors	—	—	+	—	—
Calculation complexity		Low	Low	Medium	Medium	High

‘+’: Metric works

‘•’: Metric works for QPSK, but not for higher order modulations

‘—’: Metric cannot be calculated or does not work

### 3.6 Extensions to the DM Technique

DM technology was first proposed for securing wireless information transmission along *one* pre-specified direction only in *free space*. It is natural to consider developing multi-beam DM systems and also extending DM application to multipath scenarios. These two aspects are addressed separately below.

#### 3.6.1 Multi-beam DM

Multi-beam DM transmitters have the capability of projecting multiple independent information data streams into different spatial directions, while simultaneously distorting information signal formats along all other unselected directions. The first multi-beam DM synthesis attempt was based on analogue excitation reconfigurable

DM transmitter architecture with 2-bit phase shifters [39]. Here the limited states of the phase shifters reduce the number of independent users that can be supported in the DM systems. Further in [40,41] the orthogonal vector approach was successfully adapted for general-case multi-beam DM synthesis. By realising that the orthogonal vectors generate far-field radiation patterns, termed as interference patterns, which have nulls along all desired secure directions, the far-field pattern separation approach was developed [33]. All of the above methods are equivalent.

It is worth noting that a recent study in [42] revealed that the DM system can be regarded as a kind of multiple-input and multiple-output (MIMO) system. It is well known that under multipath rich wireless channel conditions systems which deploy both multiple transmit and multiple receive antennas provide an additional spatial dimension for communication and yield degree-of-freedom gain. The additional degree-of-freedom can be exploited by spatially multiplexing several parallel independent data streams onto the MIMO channel leading to an increase in channel capacity [43]. In order to retain MIMO spatial multiplexing in free space, the multiple receive antennas have to be separately placed along different spatial directions [43].

In MIMO systems firstly the singular value decomposition (SVD) is performed on the channel matrix  $[\mathbf{H}]$  which can be obtained through channel training beforehand, i.e.,

$$[\mathbf{H}] = [\mathbf{U}][\mathbf{\Sigma}][\mathbf{V}]^\dagger. \quad (3.19)$$

Here  $[\mathbf{U}]$  and  $[\mathbf{V}]$  are unitary matrices, and  $[\mathbf{\Sigma}]$  is a matrix whose diagonal elements are non-negative real numbers and whose off-diagonal elements are zero. Then by designing networks  $[\mathbf{V}]$  and  $[\mathbf{U}]^\dagger$  and inserting them into transmit and receive sides, respectively, the MIMO multiplexing channels whose gains are diagonal entries in  $[\mathbf{\Sigma}]$ , are created.

In contrast in DM systems the receivers do not have knowledge about the channel matrix  $[\mathbf{H}]$ , and also they cannot collaborate for signal processing. Under these prerequisites the channel SVD is not applicable. Instead the channel matrix has to be decomposed as

$$[\mathbf{H}] = [\mathbf{Z}]^{-1}[\mathbf{Q}], \quad (3.20)$$

where  $[\mathbf{Z}]$  is the DM-enabling matrix (network) at transmit side, and  $[\mathbf{Q}]$  is a diagonal matrix, whose diagonal entries, similar to those in  $[\mathbf{\Sigma}]$ , represent the gains of the multiplexing channels associated with each independent receivers. The decomposition in (3.20) is not unique, which should be determined according to the system requirements, such as the gain for each receiver and the hardware constraints at transmit side.

The establishment of a link between the DM and MIMO technologies is of great importance since it may open a way for further DM development, e.g., DM operation in a multipath environment, as discussed in the following subsection.

### 3.6.2 *DM in a Multipath Environment*

‘Spatial direction’ only makes sense for free space communication, in terms of where receivers locate. In a multipath environment a more relevant concept is that of a channel that determines the response each receiver detects. Thus the extension of the DM technology for multipath application can be readily achieved by replacing the transmission coefficients in free space, which are functions of spatial directions, with the channel responses in multipath environment, which are functions of spatial positions. In [44, 45] examples were provided for the extension of the orthogonal vector approach for multipath environment with the realisation facilitated by RDAs [34] that have the ability to obtain the required channel response automatically. Other DM synthesis methods could have equally been adapted in a similar way for multipath applications.

## 3.7 **DM Demonstrators**

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Up to date there have been only a few DM demonstrators built for real data transmission.

The first demonstrator was constructed based on the passive DM architecture in 2008 [8]. Since there are no effective synthesis methods associated with this type of DM structure, as was discussed in Section 3.2, no further developments in this branch has been subsequently reported.

Instead of radiation structure reconfigurable DM, the excitation reconfigurable DM array demonstrator was built based on the analog approach in [10]. Since the iterative BER-driven synthesis approach was adopted, only the static DM transmitter was realised.

A 7-element digital DM demonstrator for 2.4 GHz operation [5] was realized with the help of the Wireless Open-Access Research Platform (WARP) [46]. This digital DM architecture is compatible with any of the synthesis methods presented in Sections 3.4.

The other DM demonstrator [7] that can be considered as hardware realizations of the orthogonal vector DM synthesis approach, utilised the beam orthogonality property possessed by Fourier beamforming networks to orthogonally inject information and interference along the desired secure communication direction. This structure avoids the use of analogue reconfigurable RF devices, thus leads to an effective step toward practical field applications. Several system level experiments based on a 13-by-13 Fourier Rotman lens for 10 GHz operation were conducted in an anechoic chamber. One is for amplitude modulation (AM), the video of which can be found in [16]. Another Fourier Rotman lens DM experiment employed WARP boards, which allowed the digital modulation to be adopted and BER to be mea-

sured [7]. The experimental setup and the results for both received constellation patterns and BER spatial distributions can be found in [7].

The properties of the four DM demonstrators are summarized in Table 3.3.

*Table 3.3: Summary of four DM demonstrators for real-time data transmission [4]. (©2015 Cambridge University Press and the European Microwave Association. Reprinted with permission from Ding Y. and Fusco V. “A review of directional modulation technology”. International Journal of Microwave and Wireless Technologies. 2015;1-13)*

Article	[8]	[10]	[5]	[7]
DM architecture	NFDAM	Antenna-reconfigurable	Digital	Fourier lens
No. of array elements	900	4	7	13
Synthesis method	Trial and error	BER-driven	Orthogonal vector	Not required
Static or dynamic DM	Static	Static	Dynamic	Dynamic
Signal modulation	Non-standard	QPSK	DQPSK	DQPSK DBPSK
Operating Frequency	60 GHz	7 GHz	2.4 GHz	10 GHz
Bit rate	Not specified	200 Kbps	5 Mbps	5 Mbps
Realisation complexity	High	Medium	Medium	Low
Complexity of steering $\theta_0$	High	High	Low	Low
Complexity for higher order modulation	High	Medium	Low	Low
Complexity for multi-beam DM	High	High	Medium	Low
Complexity for DM in multipath	High	High	Medium	High

### 3.8 Conclusions and Recommendations for Future Studies on DM

This chapter reviewed the development in the DM technique up to the present time. Specifically Section 3.1 described the DM concept. Section 3.2 enumerated the reported DM physical architecture, whose mathematical model, synthesis approaches, and assessment metrics were, respectively, addressed in Sections 3.3, 3.4, and 3.5. Section 3.6 was devoted to the extension of the DM technology for multi-beam application and multipath environment.

Although rapid development in the DM technology has been achieved in recent years, the field is still not mature, and needs to be perfected in the following aspects;

- The vector model of the DM technology was established based on a static signal constellation pattern in IQ space. This makes the model not usable for certain modulation schemes, e.g., frequency modulation (FM) and frequency-

shift keying (FSK), which exhibit trajectories with respect to time when represented in IQ space.

- In [15], it was mentioned that it was the beam orthogonality property possessed by the Fourier transform beamforming networks that enabled the DM functionality. However, in terms of successfully constructing DM transmitters, it is required that only beam orthogonality along the desired communication direction occurs, i.e. the far-field patterns excited by the interference applied at the relevant beam ports have nulls along the direction where the main information beam projects. Whereas, the main beam projected by the interference signal applied at each beam port lies at the null of the information pattern. Alignment of the nulls in this way is not strictly required as all that is needed for DM operation is that interference occurs everywhere except along the projected information direction. This means that the strict Fourier constraint may potentially be relaxed. The extent of relaxation that can be applied could be investigated.
- Current DM technology was developed based on the assumption of narrow band signals. Wideband transmissions, such as CDMA and OFDM signals, would require new mathematical models and associated synthesis methods.
- Assessment metrics and power efficiency concepts may need to be revisited when recently emerged multi-beam DM systems are under consideration.
- More synthesis-free DM transmitters that can function in multi-beam mode within multipath environment are to be expected. Furthermore associated physical implementations and experiments on real-time data transmission are of works of interest.
- More suitable candidates for multi-port antenna structures, acting as DM transmitter array elements, are required to further reduce the DM system complexity and physical profile, One preliminary work on this topic can be found in [47].

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